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Effect of Ground Granulated Blast Furnace Slag and Polymer Microspheres on Impermeability and Freeze-Thaw Resistance of Concrete

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Abstract

The primary objective of this study was to assess freeze-thaw resistance of concrete whose structure was modified by varying the water/binder ratio and ground granulated blast furnace slag content, and by air entrainment. The innovative method of the polymer microspheres-based air entrainment was used to provide a stable pore structure.

Test results show that the method is very effective both in providing adequate air entrainment and in improving freeze-thaw resistance of concrete. All air-entrained concrete specimens with polymer microspheres (the spacing factor of $\bar{L} \leq 0.25$ mm) had a good resistance to the action of frost, regardless of the W/S ratio and the slag cement content.

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Keywords: concrete; freeze-thaw resistance; air entrainment; polymer microspheres; permeability; absorption;

1. Introduction

Applications of cements containing the addition of ground granulated blast furnace slag bring considerable technical and economic benefits. Reduced pore size and improved impermeability of the paste are the main effects of the modification. Lower permeability is a major factor in marked improvement of concrete corrosion resistance. The reduction in the clinker content decreases hydration heat, which is important in massive structures, and limits alkali

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content thus preventing alkali-silica reaction in concrete. Whether concretes made with blast furnace slag are resistant to moisture, temperatures below zero and de-icing salt is an outstanding issue. According to ACI Committee 226, the addition of the slag cement should not exceed 50% due to the freeze-thaw resistance. The Polish supplements to the PN-EN 206-1 standard (PN-B-06265:2004) specify the slag amount in the exposure class XF4 as a function of CEM III class: up to 50% for 32.5R, above 50% for 42.5R and more than 80% for marine structures.

Experience shows that concretes with a slag-rich cement are extremely susceptible to damage under conditions of the combined action of frost and de-icing salts [1]. Additionaly, the study presented by Rusin et al. [4] demonstrates that concretes with GGBS cement have a markedly lower level of freeze-thaw resistance relative to the concretes made with CEM I, irrespective of W/B. Giergiczny et al. [3] reports that the use of cement containing larger amounts of slag may result in reduced total air and micropore contents in the hardened concrete and increased value of the air pore spacing factor $\bar{L}$. Deja [2] observes the worsening of the air entrainment effect in such concretes. The authors of this study [7] ascertain that an increase in the slag amount reduces the resistance to surface scaling. Test results indicate that proper air entrainment is essential to ensure good freeze-thaw resistance of concrete made with slag.

An outstanding problem in building practice is obtaining the air void structure that will be repeatable and stable in terms of both the total volume and the size of air voids [5]. Many air void instability-related problems can be avoided through the use of particles with tailored diameters, the so-called microspheres. The microspheres are used in the cement paste to introduce air voids with suitable dimensions that will not change in time. This solution is innovative in that it eliminates fundamental problems associated with coalescence and size variation of air voids. Good effectiveness of the method has been proved by the authors' own research on air entrainment of concrete mixtures with the use of polymer microspheres [6].

Ten series of concretes were tested, including non-air-entrained concretes and those air-entrained with microspheres. The analysis focused on how the three factors, namely slag cement amount added, W/B ratio and air entrainment affect the impermeability of concrete and its freeze-thaw resistance.

2. Materials and Methods

The objective of this study was to assess the physical properties and freeze-thaw resistance of concrete modified with various W/B ratios, varied content of ground granulated blast furnace slag in the binder and air entrainment. The concretes tested had the W/S ratios of 0.40-0.50.

The testing programme involved making two series of concrete (non-air-entrained and air-entrained concretes), for which the compositions were adopted according to the 5 points design, with the following factors investigated: X_1 – water/binder ratio (W/B) and X_2 – slag/cement ratio (GGBS/C). Coded variables were: X_1= (W/B – 0.45)/0.05; X_2= (GGBS/C –0.25)/0.25

The five points design is shown in Fig. 1 and the coded and real values of the factors under investigation are summarized in Table 1.

Table 1. Coded and real values of investigated factors.

Point	X_1	X_2	W/S	GGBS/C
1 (6)	-1	-1	0.40	0
2 (7)	-1	1	0.40	0.50
3 (8)	1	-1	0.50	0
4 (9)	1	1	0.50	0.50
5 (10)	0	0	0.45	0.25

The relationship is described by the regression function in the form of a non-full second degree polynomial $y = a_0 + a_1*X_1 + a_2*X_2 + a_{12}*X_1*X_2$. The correlation coefficient, R, is the measure of how well the function fits the measurement results. The experiment allows determining the relationships between factors X_1, X_2 and the given characteristic of the concrete.

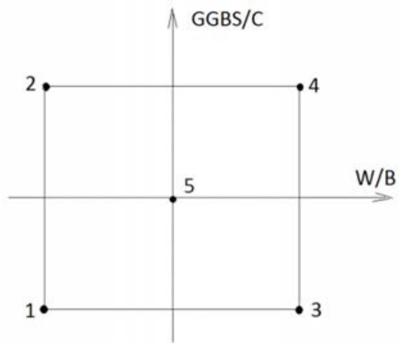

Fig. 1. Scheme of the experimental design.

The concretes were made with Portland cement CEM I 42.5 R, slag, natural sand 0 - 2 mm, coarse aggregate - basalt fraction 4 - 8, 8 - 16 mm, and polymer microspheres 40 μm for air entrainment. A plasticizer was used to obtain consistence class S4. Compositions of the concrete mixtures are shown in Table 2.

Table 2. Concrete mixture composition.

Component	Mass of components, kg/m^3									
	N-1	N-2	N-3	N-4	N-5	A-6	A-7	A-8	A-9	A-10
Cement	398	261	353	232	293	393	262	341	230	293
Slag	0	131	0	116	73	0	132	0	114	73
Water	159	157	177	174	164	157	157	171	172	164
W/B	0.4	0.4	0.5	0.5	0.45	0.4	0.4	0.5	0.5	0.45
GGBS/C	0	0.5	0	0.5	0.25	0	0.5	0	0.5	0.25
Microspheres	0	0.0	0.0	0.0	0.0	2.3	2.3	2.1	2.1	2.2

The tests were aimed at determining the compressive strength f'_{cm}, water absorption n_w, permeability Q with the use of the RCPT to ASTM C1202 – 12, freeze-thaw resistance degree F150 (dm, dR) with respect to the Polish standard PN-88/B-06250 and porosity characteristics (A, A_{300}, $\bar{L}$) according to PN-EN 480–11:1998.

The strength, water absorption and freeze-thaw resistance (resistance to internal cracking) in compliance with PN-88/B-06250 were determined on concrete cubes with dimensions 10x10x10 cm. The compressive strength of all series of concrete was determined after about 80 days of hardening (reference specimens). The test for chloride-ion penetration was performed on cylindrical specimens 9.4 cm in diameter and 5 cm in height, which were cut out of cuboids with dimensions of 15x15x20 cm. Automatic image analysis was performed using the set-up consisting of a stereoscopic microscope, a CCD camera and the motorized stage.

3. Results and Discussions

The results from the tests conducted on non-air-entrained (N-1-N-5) and air-entrained (A-6-A-10) concretes are summarized in Table 3.

Coefficients of regression and correlation coefficients were determined for both non-air-entrained and air-entrained concretes. The contour plots (Fig. 2) represent the effect of input factors, W/B (X_1) and GGBS/C (X_2), on the key properties of concrete. The selected graphs (Fig. 2 a-d) for the non-air-entrained concrete indicate that the water absorption and permeability values increase with the increasing W/B ratio. The increase in the W/B ratio leads to a lower compressive strength and freeze-thaw resistance. A change in the slag content in concrete has a minor effect on its water absorption and strength properties. The addition of the slag at the level of GGBS/C=0.5 resulted in about

50% reduction of permeability relative to the concrete without slag (GGBS/C=0). The slag content in concrete improves the resistance of specimens to freeze-thaw cycles.

Table 3. Test results for hardened concretes

Series	f'_{cm}, MPa	n_w, %	dm, g	dR, %	Q, Coulomb	A, %	A_{300}, %	$\bar{L}$ mm
N-1	99.0	4.03	13.8	29.5	2084	–	–	–
N-2	95.7	3.63	14.3	13.9	1124	–	–	–
N-3	74.8	5.38	-29.3	63.5	2727	–	–	–
N-4	73.6	4.69	17.0	20.2	1609	1.93	0.10	1.226
N-5	83.2	4.51	12.5	15.5	1670	–	–	–
A-6	85.6	4.22	3.5	2.3	2239	4.11	0.77	0.269
A-7	79.1	3.77	4.0	-2.0	1258	2.44	0.91	0.223
A-8	61.7	5.34	4.5	1.3	2940	3.45	1.59	0.175
A-9	64.8	4.67	4.5	1.9	1467	3.47	1.91	0.106
A-10	72.2	4.65	5.3	3.0	2348	3.75	1.29	0.133

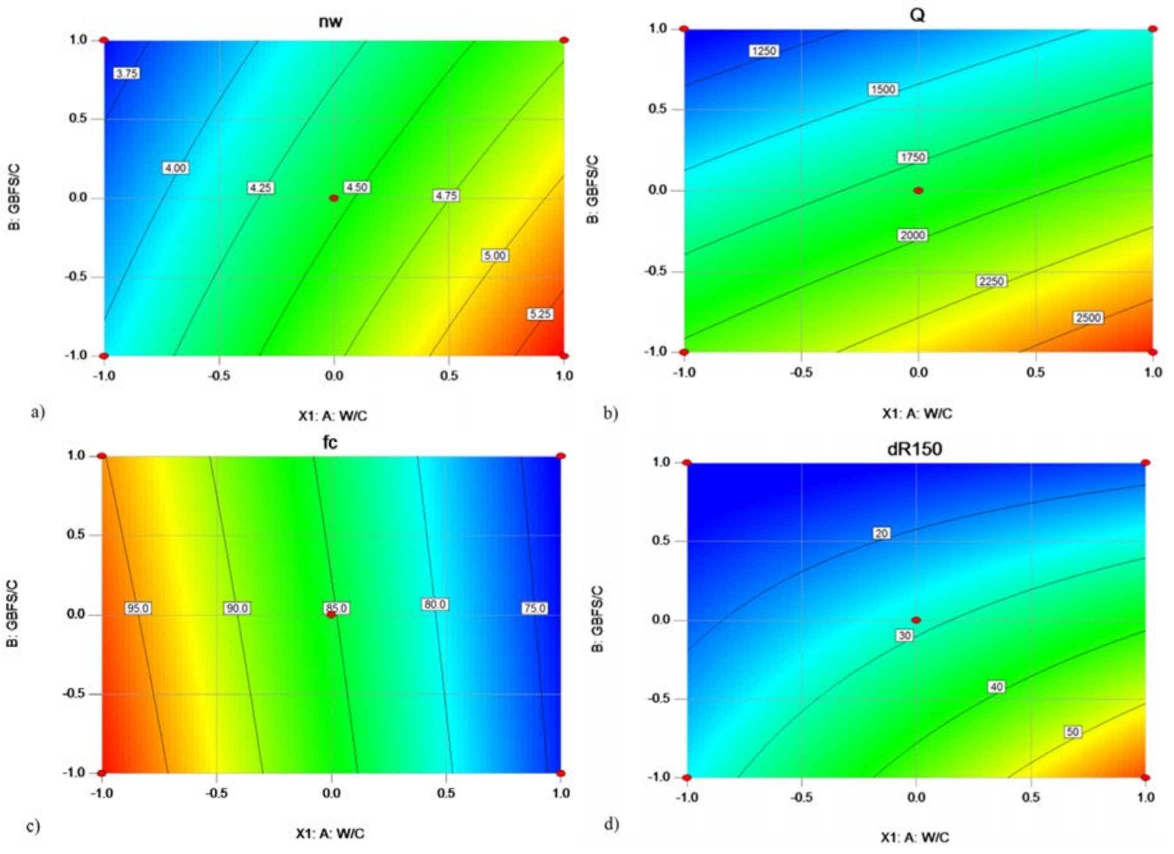

Fig. 2. Contour plots representing the effect of factors X1 and X2 on the properties of non-air-entrained concrete.

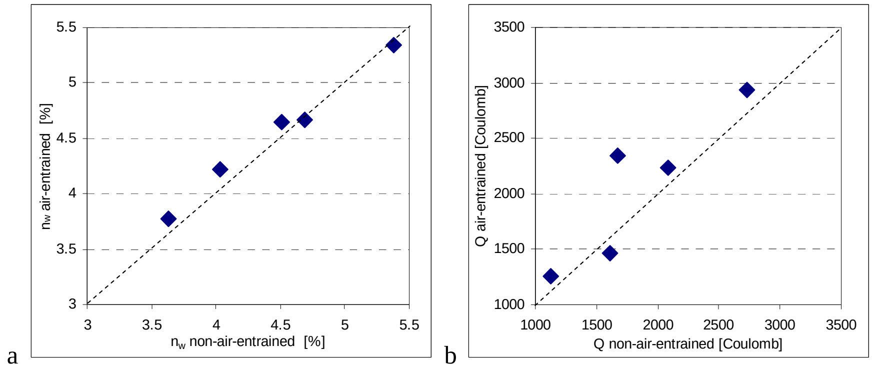

Fig. 3. Comparison of (a) water absorption; (b) permeability in non-air-entrained and air-entrained concretes.

Air entrainment of concrete mixtures has a minor effect on changes in water absorption levels (Fig. 3 a) and permeability values (Fig. 3 b), but it is a major factor in the decline of the compressive strength. Figure 4a shows a general linear dependence between water absorption and permeability of the concrete.

The test for the resistance to the action of frost (resistance to internal cracking) was performed on cubic specimens after 150 freeze-thaw cycles. The results for the change in concrete specimen mass (dm) are shown in Fig. 5. Figure 4 b illustrates the dependence between water absorption and the strength reduction in non-air-entrained and air-entrained concrete specimens after 150 freeze-thaw cycles.

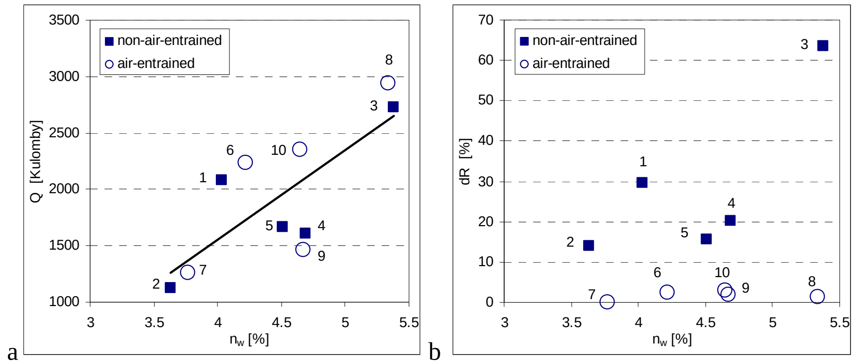

Fig. 4. Dependence between (a) water absorption and permeability, (b) water absorption and strength reduction after 150 freeze-thaw cycles.

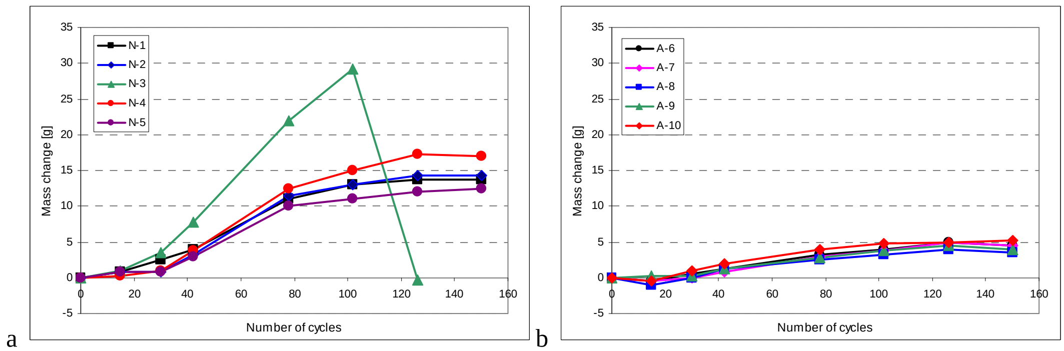

Fig. 5. Mass change of concrete (a) non-air-entrained specimens; (b) air-entrained specimens.

The non-air-entrained concrete exhibits insufficient resistance to freezing and thawing. All specimens made with this concrete showed considerable strength reduction, reaching in some cases the level of 63.5% (series N-3). A radical change in the freeze-thaw resistance of the concretes was recorded when polymer microspheres were used. All specimens made with concrete that was air-entrained with the use of polymer microspheres (series A-6-A-10) showed very good frost resistance properties.

The adopted testing methodology for freeze-thaw resistance of concrete corresponds to exposure class XF1 for concrete exposed to a moderate saturation in water without de-icing chemicals. For this exposure class, it is assumed that if the spacing factor $\bar{L} \leq 0.25$ mm, the concrete is resistant to the action of frost. Air pore structure parameters (A, A_{300}, $\bar{L}$) were determined for concrete air-entrained with polymer microspheres. The air content A ranged from 2.44 to 4.11% and the micropore content A_{300} was within 0.77-1.91%. The spacing factor $\bar{L}$ met the condition that $\bar{L} \leq$ 0.25 mm in all cases except concrete A-6, where it was slightly higher ($\bar{L}$ =0.269 mm). All air-entrained concretes showed very good resistance to frost in direct tests. This indicates that the use of polymer microspheres is an effective air entrainment method.

4. Conclusions

It was found that the increase of W/B ratio leads to the increase in water absorption and permeability, and to the decrease in compressive strength and frost resistance, as confirmed by the analysis of the results obtained from the tests of non-air-entrained and air-entrained concrete at different W/B ratios, made with the binder containing different amounts of slag. The change in the slag content in concrete has a minor effect on the water absorption and the strength of the concrete. The addition of the slag has a significant effect on the reduction of permeability and improves the resistance of the specimens to the cycles of freezing and thawing.

Air entrainment of the concrete mix with the use of polymer microspheres has a minor effect on the change in water absorption and permeability in the investigated specimens. However, air entrainment reduces the compressive strength.

Non-air-entrained concretes exhibit an insufficient resistance to freezing and thawing. The application of polymer microspheres as air entrainment caused an evident improvement in frost resistance. All air-entrained concrete specimens with polymer microspheres had a good resistance to the action of frost, regardless of the W/B ratio and the slag content. The application of the air entrainment that ensures attaining the spacing factor of $\bar{L} \leq 0.25$ mm seems sufficient to provide freeze-thaw resistance of concrete in the XF1 exposure class.

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